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Integrated GPR and laboratory water content measures of sandy soils: From laboratory to field scale

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HIGHLIGHTS

- Integrated analyses were performed to understand water content in unsaturated zone.
- We calibrated high-frequency GPR on a controlled soil column at laboratory scale.
- First reference permittivity values for sandy soils in Central Italy are given.

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ABSTRACT

In this study, laboratory and GPR water content measurements on two sandy soils are compared. A robust procedure to constrain GPR surveys is provided, aiming to obtain accurate and reliable soil moisture information at the field scale. The application of the well-known Topp's equation, provided good results only for water contents (θ_v) from 5 to 17%. Therefore, integrated analyses are mandatory to better understand the subsurface structures and the water content pattern in unsaturated zones. Data and results here presented represent the first reference for typical sandy soils outcropping in Central Italy, providing solid constraints for engineering and hydrogeological applications.

1. Introduction

Evaluation of soil moisture content (SMC) of fine grained unsaturated soils is an important target in different research fields. Its outcomes play a key role in civil engineering (i.e. road embankments, dams, earth structure, etc.), in the recharge of aquifers, in the triggering of landslides and flooding, in the agricultural irrigation and soil erosion and in the remediation of contaminated lands. Depending on the observation scale and on the aim of investigation (natural or remolded compacted soils), different techniques may be used to evaluate the SMC both in the laboratory and in the field. It is generally known that there is a wide interest in the estimation of the volumetric water content (θ_v) which is related to gravimetric water content (θ_g) by the water unit weight (γ_w) and soil dry unit weight (γ_d): the latter is an important geotechnical parameter of compacted soils [1]. Laboratory tests and indirect investigations by using not invasive equipments are commonly used to estimate θ_v. As reported by [2], SMC measurements can be carried out in situ by several techniques such as tensiometers [3], neutron moisture meters [4], capacitance sensors [5], heat pulse sensors [6], cosmic ray neutron probe [7] and the Time and Frequency Domain Reflectometry TDR/FDR [8,9]. In order to check the quality of data in term of accuracy and reliability of measurements, direct sampling from laboratory measures [10] are used for calibrating the indirect measures of water content [3]. In central Italy, TDR investigations aimed to determine the SMC and its relationship within infiltration have been widely carried out in different experimental fields [11]. Quantifying θ_v variability is difficult due to the complexity of environments and to the representativeness of spatially separated measurements [12]. TDR/FDR is a robust and precise method but it may produce soil perturbations and it is limited to a little volume, whilst remote sensing is able to cover~~s~~ large areas, but with

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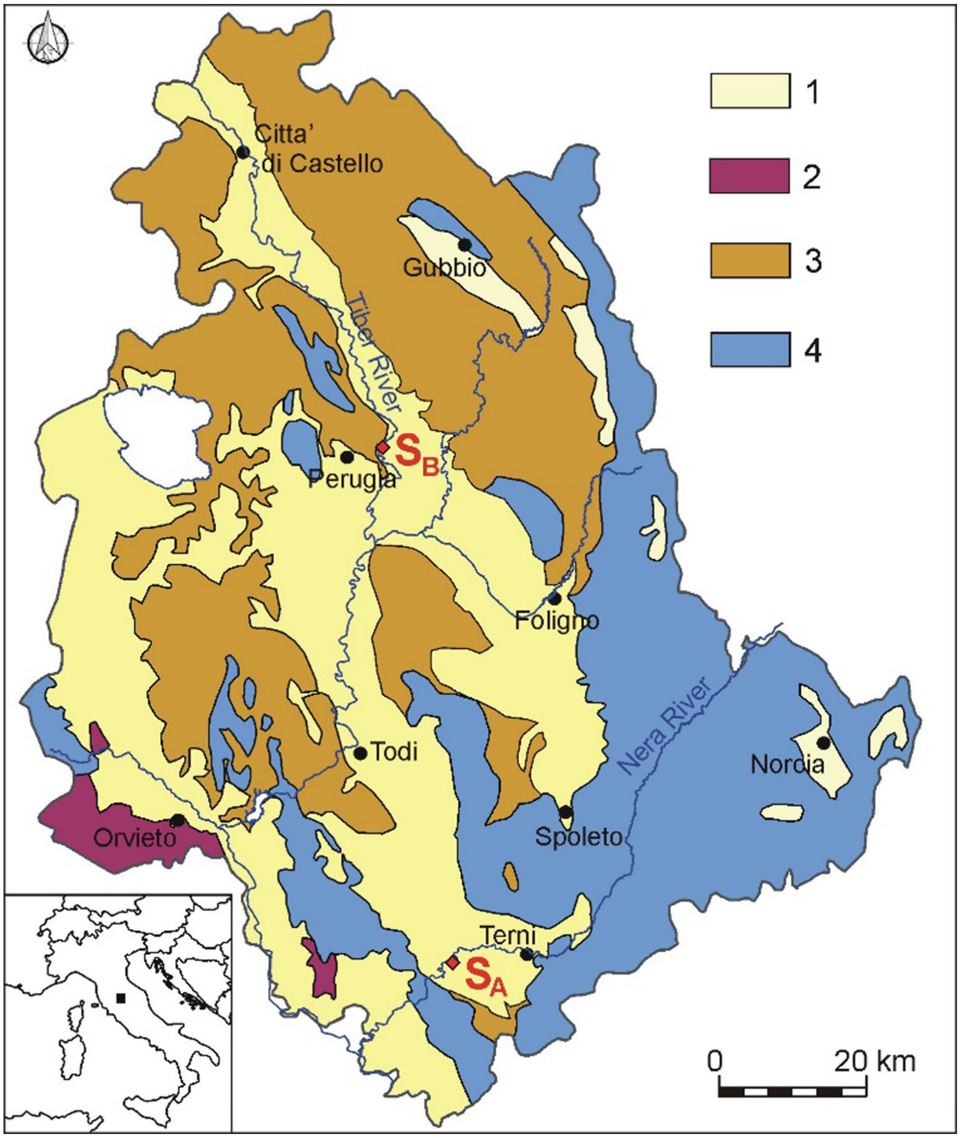

Fig. 1. Location map of sites used for soils sampling (S_A – Conca Ternana alluvial plane – Nera River, S_B – Tiber River alluvial plane). Meaning of legend of lithological map (Umbria Region, Central Italy): (1) recent and ancient fluvial-lacustrine deposits; (2) volcanic deposits; (3) flyschoid rocks; (4) calcareous and marly-silici-calcareous rocks.

Table 1
Summary of the main geotechnical properties of the two soils (modified from [44]). Gs = specific gravity of soils; γ_{dmax} = maximum dry unit weight (standard Proctor test); w_{opt} = optimum SMC (standard Proctor test); PI = plasticity index; OM = organic matter.

Soil	Grain size (%)			Gs	Compaction properties		PI (%)	OM (%)
	fines	sand	gravel		γ_{dmax} (kN/m^3)	w_{opt} (%)		
S_A	4.75	94.95	0.30	2.67	14.8	20.0	N.P.	0.37
S_B	17.59	82.41	–	2.66	17.5	13.2	N.P.	1.53

other relevant limitations [13]. Over the last years many efforts have been spent to integrate several techniques to perform non-invasive and areal measures at intermediate scales. The latter include electromagnetic induction (EMI), ground-based radiometers, electrical methods [14–16], often combined with other equipments such as the Ground Penetrating Radar (GPR) [17]. GPR has been also used by itself to provide efficient characterizations of θ_v in soils [18–21]. A comprehensive review on such a method is provided by [2,6,22,23]. Some works [21,24–28] estimated SMC using GPR reflection data. Steelman et al. [29] provide an example of soil monitoring though GPR on sand units, to derive soil hydraulic property in comparison with laboratory measurements. Bradford et al. [30] estimated the porosity of a test site by using GPR reflection tomography and borehole data. Over the last decade, new methodologies and applications have been proposed for SMC investigations, such full-waveform inversion techniques [31,32] and analysis based on spectral contents of GPR data both at the laboratory and at the real-life scales [33–35].

As stated by [36], "it is rare to have the time or financial means to revisit the same investigation site under different soil moisture conditions". Among the techniques listed above, GPR is a powerful technique suitable to guarantee a sufficient repeatability of punc-

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